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Research article

In-situ infiltration performance of different permeable pavements in a employee used parking lot – A four-year study

Kuldip Kumar*, Joseph Kozak, Lakhwinder Hundal, Albert Cox, Heng Zhang, Thomas Granato

Monitoring and Research Department, Metropolitan Water Reclamation District of Greater Chicago, 6001 West Pershing Road, Cicero, IL 60804, USA

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A B S T R A C T

Permeable pavements are being adopted as a green solution in many parts of the world to manage urban stormwater quantity and quality. This paper reports on the measured in-situ infiltration performance over a four-year period since construction and use of three permeable parking sections (permeable pavers, permeable concrete and permeable asphalt) of an employee car parking lot. There was only a marginal decline in infiltration rates of all three pavements after one year of use. However, between years two to four, the infiltration rates declined significantly due to clogging of pores either by dry deposition of particles and/or shear stress of vehicles driving and degrading the permeable surfaces; during the last two years, a greater decline was also observed in driving areas of the parking lots compared to parking slots, where minimal wear and tear are expected. Maintenance strategies were employed to reclaim some of the lost infiltration rate of the permeable pavements to limited success. Despite this decline, the infiltration rates were still four to five times higher than average rainstorm intensity in the region. Thus, these permeable pavement parking lots may have significant ecological importance due to their ability to infiltrate rainwater quickly, reduce the runoff in the catchment area, and also dampen runoff peak flows that could otherwise enter the collection system for treatment in a combined sewer area.

1. Introduction

Since the early 19th century, most urbanized areas capture and convey wastewater via a networked collection system. Many areas accommodate both stormwater and wastewater in combined sewer systems (Scholz and Grabowiecki, 2007). Population growth and urbanization have resulted in increases in impervious areas in the last three decades in many cities. This, along with changing weather patterns throughout the world, has led to tremendous impacts on local hydrology as urban areas shed more water as runoff, thereby rendering the old combined sewer systems inefficient and undersized. Additionally, many water reclamation plants (WRPs) that serve combined sewer systems need capacity expansions to treat this additional water. The upgrades needed to accept all the generated water, as well as treat the water in the centralized WRPs, are very costly.

In Chicago, Illinois, development and urbanization have altered the drainage system resulting in greater volumes of stormwater runoff and flashier storm peaks, which overwhelm the capacity of combined sewers and cause localized flooding, flow surge to the downstream WRPs, and combined sewer overflows to receiving waters. In order to minimize the impact of urban stormwater runoff pollution and the costs of control associated with wet-weather flows, stormwater runoff volumes and pollutant loads must be reduced through stormwater management. Recently, focus is shifting from 'end-of-pipe' traditional drainage systems to more sustainable drainage systems often referred to as 'Green infrastructure' (GI) for managing stormwater runoff. The impact of GI is most commonly evaluated in terms of its ability to reduce the total volume of stormwater and peak flow or delay the arrival of water that reaches the sewer system and subsequently the WRPs and receiving surface water bodies. Reducing the peak flow is also advantageous in terms of potential subsequent reduction in combined sewer overflows and localized flooding. A final benefit may also be realized by reducing pollutants being conveyed to surface water bodies via WRPs hence reducing the impact of the 'first flush' effect that is commonly associated with urban runoff (Rajapakse and Ives, 1990; Andersen et al., 1999; Drake et al., 2014; Mullaney and Lucke,

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* Corresponding author.
E-mail address: Kuldip.Kumar@mwrd.org (K. Kumar).

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2014). These GI technologies have shown reductions in the concentration of suspended solids, biochemical oxygen demand, ammonia, hydrocarbons, and mineral oil in stormwater (Baladès et al., 1995; Pratt et al., 1999; Bean et al., 2007; Drake et al., 2014).

The general principle behind the idea of GI technologies, and permeable pavements in particular, is simply "collect, treat, and freely infiltrate stormwater to recharge groundwater" such that the stormwater bypasses the collection system sewers. In comparison to traditional drainage systems, GI technologies are deemed sustainable and are often cost effective for urban areas.

Permeable pavements are one such GI technology that is being adopted to manage stormwater in many urban areas in both Europe and the United States (Baladès et al., 1995; Brattebo and Both, 2003; Bean et al., 2004; Scholz and Grabowiecki, 2007; Mullaney and Lucke, 2014). The infiltration performance throughout the service life of permeable pavement is of important significance as entrapment of fine particulate matter (both organic and inorganic) in the pores of the pavement surfaces may cause irreversible reduction of water permeability (Borgwardt, 2006; Scholz and Grabowiecki, 2007; Sansalone et al., 2012; Yong et al., 2013) and ultimately reduce their effectiveness. Nevertheless, these permeable pavement systems may have significant impact on the runoff process. Even if part of the rainfall is retained, this part is not added to the total runoff entering the collection system. A reduction in runoff peaks can also occur because of the pavement's delaying effects (Borgwardt, 2006). Lee et al. (2010) and Montalto et al. (2007) conducted a cost-effectiveness analysis on stormwater best management practices and showed that permeable pavements were most cost effective in managing runoff, reducing peak flows and delaying peak runoff time as compared to green roofs and traditional storage basins and traditional drainage systems.

The research reported herein involved the evaluation of three different kinds of permeable pavement installed into sections of a parking lot at the Stickney WRP of the Metropolitan Water Reclamation District of Greater Chicago (MWRDGC). The pavements used were (i) permeable asphalt, (ii) permeable concrete, and (iii) permeable pavers. This research reports the temporal changes in water infiltration into these respective permeable pavements since their construction and four years of use as well as spacial differences in infiltration rate changes that have occurred in different sections of the pavements that have undergone different degrees of use.

2. Site description and methods

2.1. Description of permeable pavements in parking lots of MWRDGC's Stickney WRP and site description

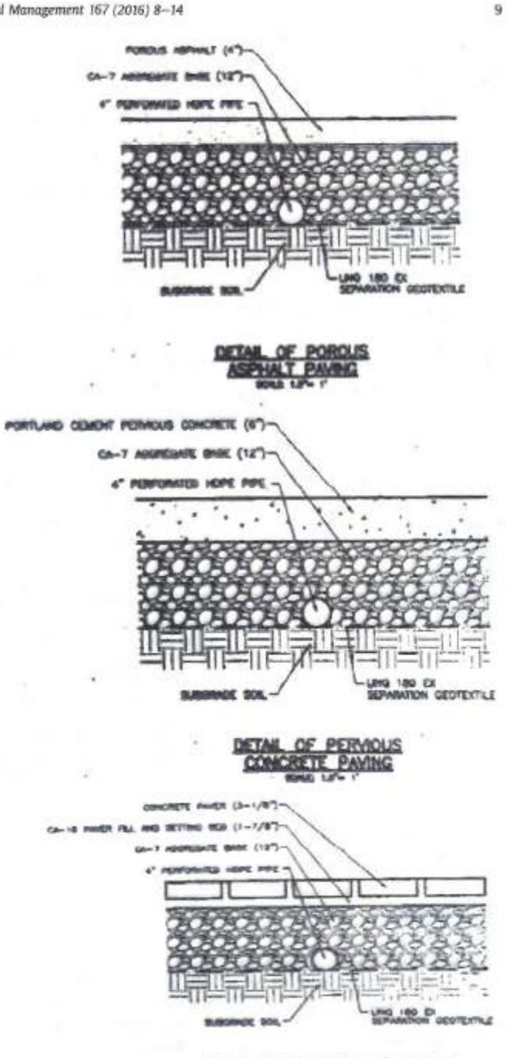

Fig. 1. Design details of the permeable pavers, permeable concrete and permeable asphalt lots of the parking lot at the Stickney Water Reclamation Plant.

The permeable parking surfaces that were constructed on the existing employee parking facility measure approximately 245.8 m × 82.1 m in total (Picture 1). The existing parking facility had six sections. The easternmost section was divided into two with a ~6 m grassed median separating the two sections with a permeable pavers lot on the south side and a permeable concrete lot on the north side. The permeable asphalt lot was located on the southern half of the 3rd from the westernmost parking section. Each parking section is separated by a 6 m wide grassed median, with through traffic moving east-west between different sections at the north side of the parking sections. The actual sizes of the permeable parking lots and number of parking stalls in each lot are given in Table 1. There are 43, 38, and 23 parking slots in permeable pavers, permeable concrete, and permeable asphalt lots, respectively (Table 1). The permeable pavers' lot receives minimum traffic, as it is used to park the MWRDGC's pollution control full-size vans and small utility vehicles with, on average, only less than 40% of the slots filled and minimum in-out traffic during the day. However, these vehicles are bigger and heavier as compared to the passenger cars used by employees. On the other hand, all slots in the permeable concrete and permeable asphalt lots are always full throughout the working days during the year. In general, MWRDGC employees park their cars for the 8.5-h work day, and only ~10% of the cars may be moved in and out during the day with employees going out during lunch break. The permeable concrete and pavers lots do not have through traffic; cars enter and leave from the same direction. The permeable asphalt lot has regular asphalt on the north side without any physical barrier in between but is sloped in

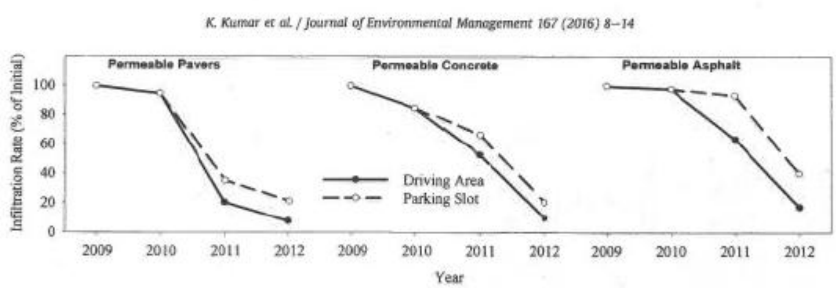

Fig. 2. Percent decline in infiltration rates of permeable pavements during the four years of use at the Stickney Water Reclamation Plant.

Picture 1. A picture showing relative location of permeable parking lots in an employee parking lot at the Stickney Water Reclamation Plant.

a way to separate the respective catchment areas and receive car traffic from both sides; however, all cars leave the parking lot from the south side only. The lots receive different contributions of run-on from permeable and impermeable surrounding surfaces during rainfall events and are allowed to drain freely towards the local groundwater (Table 1). The construction of permeable lots was completed in fall 2008, and they were opened to traffic in spring of 2009. Each year during winter, snow from these parking lots was removed using a skid-steer machine with a snowplow blade on it, and de-icing salt (mixture of chloride salts of sodium, calcium and magnesium) was also used as in the normal parking lot. Maintenance involved sweeping the lots with a general street sweeper twice annually. Mean annual precipitation at the study site for the four years between 2009 and 2012 was 107.1 cm, 92.4 cm, 122.8 cm, and 67.6 cm respectively.

2.2. *Porous asphalt*

The porous asphalt used looks similar to conventional asphalt; it consists of open-graded asphalt (10-cm layer) over an open-graded fill base 30 cm deep, consisting of CA-7 aggregates above native soil (Fig. 1 and Picture 2a). The aggregate base was separated from subgrade native soil by LINQ 180 EX separation geotextile.

2.3. *Porous concrete*

The porous concrete pavement used (15-cm thick) was set in place using CA-16 Class A coarse aggregates, which are freeze-thaw durable, and a Portland cement binder over an open-graded CA-7 aggregate base 30 cm deep. The pavement's porosity is a result of the omission of fine aggregates in the concrete mix. The aggregate

Table 1

Description of the permeable pavement lots of the car parking lot at the Stickney Water Reclamation Plant.

Characteristics	Permeable pavers	Permeable concrete	Permeable asphalt
Size (m^2)	1216	1060	1311
Additional run-on area			
Impervious (m^2)	38	336	31
Pervious (m^2)	0	539	0
Parking slots			
Regular (3.05 m × 5.80 m)	43	38	23
Disability (4.88 m × 5.80 m)	0	0	5
Through traffic	No	No	Yes

(a) Permeable Asphalt

(b) Permeable Concrete

(c) Permeable Pavers

Picture 2. Pictures of permeable pavement sections (a) asphalt, (b) concrete, and (c) pavers in an employee parking lot at the Stickney Water Reclamation Plant when opened for use in May, 2009.

base was separated from the subgrade native soil by LINQ 180 EX separation geotextile (Fig. 1 and Picture 2b).

2.4. Permeable pavers

The permeable pavers used were made of concrete ~7.8 cm thick overlaying a ~4.8 cm thick layer of CA-16 paver fill bed. The pavers were interlocking with apertures between the pavers that were filled with the CA-16. Similar to the permeable asphalt and concrete, the base consisted of 30 cm deep CA-7 aggregates separated from the native subgrade soil by LINQ 180 EX geotextile (Fig. 1 and Picture 2c).

2.5. Infiltration rate measurement

The ASTM C1701 method was used to measure the infiltration rate of permeable surfaces. The method was developed by ASTM Technical Committee C09 for pervious concrete surfaces. The equipment required for ASTM C1701 measurements is currently not available commercially. A double-ring infiltrometer used in this study consisted of two 16 gauge galvanized steel rings. The inner ring had an inner diameter of 30 cm and was 75 cm tall, while the outer ring had a diameter of 60 cm and was 60 cm tall. The rings were sealed to the permeable surface using plumber's putty or alginate. The details of the ASTM C1701 method are provided in Li et al. (2013). The tests were repeated at four random spots in a lot for the first two years. During the third and fourth years, tests were conducted separately on the driving areas and within the parking slots of each lot with four and five replications, respectively. These surface inundation tests do not prevent horizontal migration of the water once it enters the pervious surface. However, it is assumed that most of the water drained directly downward into the pavement and underlying aggregate fill.

2.6. Statistical analysis

The infiltration rate data set was analyzed using the MIXED procedure of SAS (SAS Institute Inc., 1989). Tests of significant differences of the infiltration rates between the lots over the four-year study period, between each lot from year to year, and collectively between driving area and parking slots for the four years of the study were performed. Residuals were tested for assumptions of ANOVA; namely, that the transformed data were normally distributed and groups had homogeneous variances (Sokal and Rohlf, 1995). Means were separated using Duncan's multiple range tests at $P \leq 0.05$. Percent reductions over the four-year study period were also calculated for each lot.

3. Results and discussion

3.1. Pavement condition evaluation

Noticeable wear and tear was observed after the permeable parking lots were constructed and put to use for employee car parking since 2009, as discussed below.

3.2. Permeable asphalt

The end of the 2010 evaluation indicated that this lot was in relatively good condition. There was no vegetation identified, but some surficial sediment buildup in small areas along the eastern border and northwest corner of the lot was observed. Additionally, cuts and scours caused by snowplowing were observed. Minor raveling, i.e. progressive disintegration of the pavement causing large particles to dislodge, was also observed. The 2011 evaluation revealed no vegetative growth but that raveling had increased, especially in the driving lanes and southern entrance. The raveling increased significantly in the driving areas in 2012, as compared to previous years, and some raveling was also observed in parking slots (Picture 3). Once raveling occurred at the surface, it worsened with time due to daily traffic and also winter snowplowing.

3.3. Permeable concrete

The 2010 evaluation indicated that this lot was in relatively good condition with only minor vegetative growth along the edges of the lot. Minor raveling and some cracking was also observed. The 2011 evaluation revealed vegetation along the borders of the lot necessitating weeding, major raveling around the control joints along the perimeter of the lot, and two large cracks in the center of the lot. By the end of 2012, increased raveling was observed in driving areas as compared to previous years; the area between parking slots had only minor raveling (Picture 3).

3.4. Permeable pavers

The 2010 evaluation indicated that this lot was in the worst condition of the three permeable pavement lots. Multiple locations of chipped pavers and vegetation growing between the pavers were observed. Pronounced depressions were noted throughout the lot. Additionally, the fill between the pavers was noticeably missing in a number of locations. The 2011 evaluation revealed weeds in the corners of the lot necessitating weeding and an increased number of chipped, spalled, and cracked pavers. The 2012 evaluation showed more degradation than was observed in 2011 and little vegetation that needed weeding (Picture 3). In addition, an oil leak patch of approximately 1 m^2 area was also observed in one slot.

By the end of 2012, the relative condition from best to worst was in the order of: permeable concrete > permeable pavers > permeable asphalt. This may be related to higher traffic in the asphalt lot due to vehicles leaving and entering from both sides of the lot, while the pavers and concrete lots were isolated and did not have through traffic. The depressions observed in the pavers lot may be due to the relatively heavier utility vehicles parked in this lot as compared to passenger cars in the other sections.

3.5. Infiltration rate evaluation of the parking lots

The overall infiltration performance of the permeable pavements was considered to depend on the permeability or porosity of the surface permeable layer, which in the present case are concrete, asphalt, and pavers. The infiltration rates of these surfaces were very high when these parking lots were constructed and opened for use in 2009. In 2009, the average infiltration rates in decreasing order were: concrete (38.2 mm s^{-1}) > asphalt (31.1 mm s^{-1}) > pavers (25.4 mm s^{-1}) (Table 2). Infiltration rates after one year of use (2010)

Drive Area Parking Slot

(a) Permeable Asphalt

Drive Area Parking Slot

(b) Permeable Concrete

Drive Area Parking Slot

(c) Permeable Pavers

Picture 3. Pictures of permeable parking sections (a) asphalt, (b) concrete, and (c) pavers taken in December, 2012 showing deterioration of surface in driving areas as compared to parking slots.

did not decline significantly for the pavers and asphalt lots; however, the rate declined significantly for the concrete lot from 38.2 to 32.5 mm s^{-1}. For 2010, infiltration rates of the concrete and asphalt lots were similar but still significantly higher than pavers (Table 2). During the third year of use (2011), infiltration rates of all three permeable surfaces declined significantly, but the decline was much more drastic for the pavers lot, which declined from 24.1 mm s^{-1} in 2010 to 7.1 mm s^{-1} in 2011 (Table 2). Additionally, during the fourth year (2012), the infiltration rates declined for all lots; but the rate declines were much greater for the concrete and asphalt lots (Table 2).

There was no difference in infiltration rates with respect to the different spatial locations and use (driving area versus parking slot) for all three pavement lots for the first two years (2009 and 2010). However, during the third year (2011), infiltration rates were significantly lower in the driving areas (15.2 mm s^{-1}) as compared to 20.9 mm s^{-1} in the parking slots (Table 2). These differences between the driving areas and parking slots became more prominent during the fourth year (2012), i.e. the infiltration rate being more than 50% lower in driving areas as compared with parking slots (Table 3). The reason for the decline in the infiltration rate with time is most likely linked to clogging of the pores of the pavements. This clogging not only reduces the total pore space volume but may also block the pores, thereby reducing their connectivity and ultimately hindering the flow of water. Similar reductions in infiltration of permeable pavements within three years after installation have been reported in earlier studies (Bean et al., 2004; Scholz and Grabowiecki, 2007; Sansalone et al., 2012). The main causes of clogging may be (i) particulate matter from dry deposition, particles from tire wear, or car exhausts entering the pores; (ii) waterborne particulate matter which drains into porous pavement clogs the pores; (iii) shear stress on the surfaces caused by driving of vehicles; this may cause collapse of the surface resulting in a grinding effect producing fine particles as well as collapsing of bigger voids; (iv) freeze-thaw of surfaces may also cause deterioration; and (v) an oil leak may also block the pores or make the voids hydrophobic and thus impeding water movement.

In fact, we measured the infiltration rate in a parking slot in the permeable paver lot in 2012 where oil leaked (see Picture 3c) and observed the infiltration rate of only 0.38 mm s^{-1}, which was ten times lower than the mean infiltration rate in pavers measured at the same time in 2012. For this particular site, dry deposition is considered the most significant cause for clogging. The urban areas in Chicago, Illinois, are reported to have much higher mass fluxes of dry deposition compared to smaller cities. Franz et al. (1998) reported mass flux of dry deposition in the area of the study site varied from 34 to 200 mg m^{-2} d^{-1}, which is significantly higher as compared to 1.2–28 mg m^{-2} d^{-1} in smaller cities. Additionally, shear stress caused by vehicle operation may have also played a role. This latter cause is the suspected reason that infiltration rates from the third year (2011) onwards declined at a much higher rate in driving areas as compared to parking slots (Table 3 and Fig. 2).

Table 2

Comparison of infiltration rates (mm sec^{-1}) of various permeable pavements in a routinely used car parking lot at the Stickney Water Reclamation Plant during four years of monitoring period.

Year	Permeable pavers	Permeable concrete	Permeable asphalt
2009	25.4cA†	38.2aA	31.1bA
2010	24.1bA	32.5aB	30.6aA
2011	7.1bB	22.7aC	24.4aB
2012	3.8cC	6.0bD	9.1aC

†Numbers followed by a different lowercase letter in a row and uppercase letter in a column are significantly different according to Duncan's Multiple Range Test at $P \leq 0.05$.

Table 3

Infiltration rates (mm sec^{-1}) of permeable pavements in driving areas and parking slots during the third and fourth year of use at a car parking lot of the Stickney Water Reclamation Plant.

Year	Driving area	Parking slot
2011	15.2bA†	20.9aA
2012	3.9bB	8.7aB

†Numbers followed by a different lowercase letter in a row and uppercase letter in a column are significantly different according to Duncan's Multiple Range Test at $P \leq 0.05$.

While evaluating four permeable pavement surfaces after six years of usage, Booth and Leavitt (1999) did not notice major signs of wear or decrease in infiltration. However, many other studies have shown as much as a 35–50% reduction in infiltration rates after two to three years of usage of permeable parking lots (Baladès et al., 1995; Mullaney and Lucke, 2014). These same authors referred to a study conducted by the French Ministry of Works Central Laboratory showing that clogging developed within the first year on permeable roads; decline was related to traffic intensity and pollution levels, causing a 30–50% decline in infiltration rate in country areas, 40–70% in cities, and 60–90% in very polluted areas.

The results from the present study showed only marginal (between 2 and 15%) declines in infiltration rates after one year of usage (2009 thru 2010), after which the declines accelerated for all three surfaces (2010 thru 2012) (Fig. 2). In the fourth year (2012), the infiltration rates had declined by as much as 82–90% in the driving areas and by 60–79% in the parking slot areas relative to year one (2009) (Fig. 2). Nonetheless, the minimum infiltration rate of 3.8 mm s^{-1} observed after four years of usage of the worst performing lot (permeable pavers lot) was 380 times higher than the 0.01 mm s^{-1} intensity of a five-year, 1-h rainstorm in the study area (Hershfield, 1961). Thus, no runoff is expected, or in fact has ever been observed, during site visits in these permeable sections of the parking lot at the Stickney WRP (data not reported).

It is clear that with time, infiltration rates of permeable pavements decline, and declines are greater in places with greater traffic, as shown in comparison of parking slots and driving area in the present study, which may be related to higher wear and tear and greater degree of clogging of pores. Clearly, use intensity increases the rate of wear and clogging of pores, which may be much higher in commercial parking lots where traffic intensity may be much higher. Thus, as pointed out by Bean et al. (2004) and Dierkes et al. (2015), maintenance programs to prevent clogging may be very important in maintaining the high surface infiltration rates. In an interesting study using gamma rays, Baladès et al. (1995) showed that the clogged area was limited to the upper two cm of permeable surfaces tested. In general, four methods of maintenance are available for maintaining permeable pavements: (1) gentle water spray of the surface followed by sweeping; (2) sweeping followed by suction; (3) suction alone; and (4) high pressure water jet washing and suction together. The maintenance program we have adopted until now has been a gentle water spray followed by rotary brush sweeping twice a year. In a comprehensive review of what kind of maintenance practices work better, it may be concluded that clogging can be countered by suction cleaning as a preventive maintenance and by high pressure water jet washing followed by suction as a remedial maintenance (Baladès et al., 1995; Bean et al., 2004; Dierkes et al., 2015).

4. Conclusion

By the end of 2012, the relative physical condition of permeable pavements from best to worst was in the order of: permeable concrete > permeable pavers > permeable asphalt. This may be related to higher traffic in the asphalt section due to vehicles leaving and entering from both sides of the lot, while the pavers and concrete lots were isolated and did not have through traffic. The infiltration rates of the studied permeable pavements were very high at the beginning of the four-year study but declined with time due to clogging of pores, most notably after year three. The 2012 data showed the highest infiltration rate in asphalt, followed by the concrete lot, with the minimum rate in the pavers lot. Based on our literature review, there is need to change our maintenance regime from water spray followed by sweeping to suction sweeping, or high pressure jet washing followed by suction sweeping, to restore the infiltration rates. Nonetheless, infiltration rates are still approximately 380 times higher than most of the rainstorm events impacting the study area, and no runoff flows are expected or have been observed at these permeable pavements. Thus, these permeable pavement parking lots may have significant ecological importance due to their ability to infiltrate rainwater quickly and reduce the runoff in the catchment area and also dampen runoff peak flows that may otherwise result in high influent flows to WRPs and affect operations or cause local flooding and combined sewer overflows.

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